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Calibrating A Six-Port Reflectometer with Four Impedance Standards

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Calibrating A Six-Port Reflectometer with Four Impedance Standards

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Issued March 1979

NATIONAL BUREAU OF STANDARDS TECHNICAL NOTE 1012
Nat. Bur. Stand. (U.S.), Tech. Note 1012, 24 pages (Mar. 1979)
CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1979

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
Stock No. 003-003-02036-2 Price $1.20 (Add 25 percent additional for other than U.S. mailing)

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This report is a theoretical study showing how four terminations of known impedance can be used to calibrate a six-port reflectometer for measuring other terminations of unknown impedance. The equations for obtaining the calibration constants are exact but nonlinear, requiring an iterative solution. Several ways are described for using these constants to calculate the impedance of terminations being measured with the six-port reflectometer.

Key Words: Calibration; impedance; reflection coefficient; reflectometer; six-port.

I. INTRODUCTION

A six-port reflectometer is a circuit with six ports designed to measure power and reflection coefficient at one of its ports in terms of power readings taken at four other ports when a signal is applied at the remaining port. To measure reflection coefficients with a six-port, it must first be calibrated to determine 11 constants which characterize the six-port. This paper describes a technique for determining these constants with four different terminations whose reflection coefficients are known.

Several techniques have already been published for calibrating a six-port reflectometer. Engen [1,2] has described a technique using a sliding short and a sliding load. However, at frequencies below about 100 MHz, it becomes impractical to use sliding components because their length becomes too long. It then becomes more practical to use fixed terminations which have known values of impedance. A technique for calibrating a pair of six-port reflectometers is described by Hoer [3]. This technique also becomes impractical below about 100 MHz because the standard transmission line used in the calibration procedure becomes too long. Additional work by Engen [2] has shown that it is possible to calibrate a six-port reflectometer with only three known terminations if one first reduces the six-port to an equivalent four-port. This reduction requires that the six-port sidearm power readings be recorded when a minimum of five but preferably nine different unknown terminations are connected to the reference plane. Three of this set of five to nine terminations can be the three known standard terminations. Cronson and Susman [4] have published equations for use in calibrating a six-port reflectometer with four known terminations. Their solution is a closed linear solution, but it assumes that the wave incident upon each of the four terminations is the same when they are connected to the reference plane. This assumption is not usually satisfied. The calibration procedure described below in this paper also uses four known terminations, but the solution for the calibration constants does not require that the incident wave be held constant. However, the equations then becomes nonlinear, requiring a solution which is an iteration of an approximate linear solution.

This report should be viewed as a preliminary theoretical study. Further work needs to be done to determine the relative merits of the different proposed solutions.

II. SIX-PORT REFLECTOMETER EQUATIONS

Let the six-port power detectors be labeled as shown in figure 1. It has been shown [3] that the power P_i measured at port i = 3,4,5,6 is given by

$$P_i = |A_i a + B_i b|^2 \qquad i = 3...6, \quad (1)$$

where a,b are the waves incident upon, and reflected from, the termination at the measurement reference plane, and A_i, B_i are functions of the scattering parameters of the six-port and the reflection coefficients of its four power detectors. Engen [5,6] has rewritten eq (1) in the form

$$P_i = |B_i a|^2 \, |\Gamma - q_i|^2, \qquad i = 3...6, \quad (2)$$

where Γ is the reflection coefficient of the termination at the reference plane, and the q_i are new constants describing the six-port;

$$\Gamma = b/a, \quad q_i = -A_i/B_i \ . \qquad (3)$$

The four complex q_i and three of the four $|B_i|$ are the 11 constants needed to calculate an unknown Γ from the four power readings.

For this paper it will be more convenient to write eq (1) in the form

$$P_i = |A_i \, a|^2 |1 + G_i \Gamma|^2, \qquad i = 3...6, \quad (4)$$

where

$$G_i = B_i/A_i = -1/q_i \quad .$$

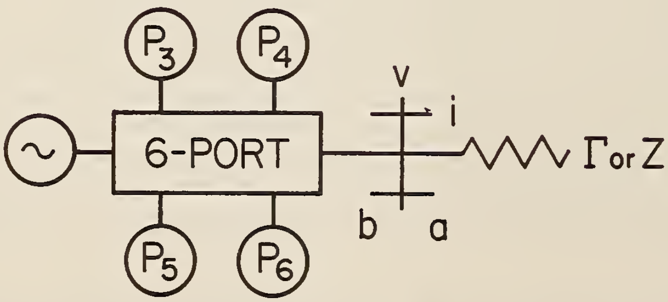

Figure 1. Six port reflectometer.

III. CALIBRATION EQUATIONS, a AND b PARAMETERS

The calibration is performed by recording each of the four P_i when four different terminations having known reflection coefficients are connected to the reference plane Add a subscript $\ell = 1,2,3,4$ to P_i, a, and Γ in eq (4) to indicate these four known terminations.

$$P_{i\ell} = |A_i\, a_\ell|^2\, |1 + G_i\, \Gamma_\ell|^2, \qquad i = 3\ldots6;\ \ell = 1\ldots4. \tag{5}$$

Let the six-port be designed and the sidearms numbered so that P_3 is primarily a function of the incident wave a. Then P_3 will never be zero and we can divide eq (5) by $P_{3\ell}$ to get

$$\frac{P_{i\ell}}{P_{3\ell}} = \frac{|A_i|^2}{|A_3|^2}\, \frac{|1 + G_i\, \Gamma_\ell|^2}{|1 + G_3\, \Gamma_\ell|^2} \qquad i = 4,5,6;\ \ell = 1\ldots4. \tag{6}$$

This ratio eliminates $|a_\ell|$ so that no assumption about the incident wave needs to be made in the calibration process.

For the first termination, eq (6) gives

$$\frac{P_{i1}}{P_{31}} = \frac{|A_i|^2}{|A_3|^2}\, \frac{|1 + G_i \Gamma_1|^2}{|1 + G_3 \Gamma_1|^2} \qquad i = 4,5,6. \tag{7}$$

Choose the first termination so that its reflection coefficient Γ_1, is such that none of the P_{i1} are zero. For most existing six-port reflectometer designs, if $\Gamma_1 \simeq 0$, none of the P_{i1} will be zero. Then dividing eq (6) by eq (7) gives

$$\delta_{i\ell} \equiv \frac{P_{i\ell}\, P_{31}}{P_{3\ell}\, P_{i1}} = \left|\frac{1 + G_i\, \Gamma_\ell}{1 + G_3\, \Gamma_\ell} \cdot \frac{1 + G_3\, \Gamma_1}{1 + G_i\, \Gamma_1}\right|^2, \qquad i = 4,5,6;\ \ell = 2,3,4, \tag{8}$$

where the $\delta_{i\ell}$ are calculated from the observed power readings. There are nine equations like eq (8) which can be solved for the four complex constants $G_3 \ldots G_6$ (8 real unknowns). The equations are nonlinear and in general an iteration procedure must be used to solve for the unknowns.

When $\Gamma_1 \simeq 0$, the remaining three terminations should be highly reflecting and have values of Γ whose phase angles are perferably in different quadrants.

A. Iterative Solution for the G_i

To simplify the solution of eq (8) for the four G_i, define

$$g_{i\ell} \equiv |1 + G_i\, \Gamma_\ell|^2, \qquad i = 3\ldots6, \tag{9}$$

and let the components of G_i and Γ_ℓ be

$$G_i \equiv G_i' + j\, G_i'' , \qquad i = 3\ldots6, \tag{10}$$

$$\Gamma_\ell \equiv \Gamma_\ell' + j\,\Gamma_\ell'' , \qquad \ell = 1...4. \quad (11)$$

Expanding eq (9) with eq (10) and eq (11) leads to

$$g_{i\ell} = |1 + G_i\Gamma_\ell|^2 = 1 + 2G_i'\Gamma_\ell' - 2G_i''\Gamma_\ell'' + |G_i|^2\,|\Gamma_\ell|^2 . \quad (12)$$

Using eq (9), eq (8) can be rearranged and written as

$$\delta_{i\ell}g_{3\ell}\,g_{i1} = g_{i\ell}g_{31}, \qquad \begin{array}{l} i = 4,5,6 \\ \ell = 2,3,4. \end{array} \quad (13)$$

Next define $f_{i\ell}$ as

$$f_{i\ell} = \delta_{i\ell}g_{3\ell}\,g_{i1} - g_{i\ell}g_{31} = 0, \qquad \begin{array}{l} i = 4,5,6; \\ \ell = 2,3,4, \end{array} \quad (14)$$

and expand $f_{i\ell}$ in a Taylor series [7] about the best estimates of G_3 and each G_i. Keeping only linear terms, eq (14) becomes

$$f_{i\ell} = f_{oi\ell} + \frac{\partial f_{i\ell}}{\partial G_3'}\Delta G_3' + \frac{\partial f_{i\ell}}{\partial G_3''}\Delta G_3'' + \frac{\partial f_{i\ell}}{\partial G_i'}\Delta G_i' + \frac{\partial f_{i\ell}}{\partial G_i''}\Delta G_i'' = 0, \qquad \begin{array}{l} i = 4,5,6; \\ \ell = 2,3,4, \end{array} \quad (15)$$

where $f_{oi\ell}$ is the value of $f_{i\ell}$ calculated from eq (14) using best estimates of G_3 and G_i. The partial deriatives in eq (15) are obtained from eq (14);

$$\frac{\partial f_{i\ell}}{\partial G_3'} = \delta_{i\ell}\frac{\partial g_{3\ell}}{\partial G_3'}\,g_{i1} - g_{i\ell}\frac{\partial g_{31}}{\partial G_3'}$$

$$\frac{\partial f_{i\ell}}{\partial G_3''} = \delta_{i\ell}\frac{\partial g_{3\ell}}{\partial G_3''}\,g_{i1} - g_{i\ell}\frac{\partial g_{31}}{\partial G_3''}$$

$$\frac{\partial f_{i\ell}}{\partial G_i'} = \delta_{i\ell}\,g_{3\ell}\frac{\partial g_{i1}}{\partial G_i'} - \frac{\partial g_{i\ell}}{\partial G_i'}\,g_{31} \qquad \begin{array}{l} i = 4,5,6; \\ \ell = 2,3,4, \end{array} \quad (16)$$

$$\frac{\partial f_{i\ell}}{\partial G_i''} = \delta_{i\ell}\,g_{3\ell}\frac{\partial g_{i1}}{\partial G_i''} - \frac{\partial g_{i\ell}}{\partial G_i''}\,g_{31}$$

where from eq (12),

$$\frac{\partial g_{i\ell}}{\partial G_i'} = 2\Gamma_\ell' + 2\,G_i'|\Gamma_\ell|^2$$

$$\frac{\partial g_{i\ell}}{\partial G_i''} = -2\Gamma_\ell'' + 2\,G_i''|\Gamma_\ell|^2 \qquad \begin{array}{l} i = 3...6; \\ \ell = 1...4. \end{array} \quad (17)$$

These partial derivatives are calculated using the same best estimate of G_3 and G_i used in calculating $f_{oi\ell}$.

The nine equations represented by eq (15) are solved for the eight unknown $\Delta G_i'$ and $\Delta G_i''$. Since the equations are linear in these unknowns, the solution is straightforward. One solution is outlined in Appendix A. The $\Delta G_i'$ and $\Delta G_i''$ are then used to improve the previous estimate of the G_i' and G_i''.

$$\text{new } G_i' = \text{old } G_i' + \Delta G_i'$$

$$\text{new } G_i'' = \text{old } G_i'' + \Delta G_i'' \qquad i = 3 \ldots 6. \quad (18)$$

These new estimates of G_i' and G_i'' are used to compute new $f_{oi\ell}$ and partial derivatives. The solution of eq (15) is then repeated for a new set of $\Delta G_i'$ and $\Delta G_i''$. The iteration is continued until the $\Delta G_i'$ and $\Delta G_i''$ become insignificant.

B. Initial Estimate of the G_i

Since the solution of eq (8) for the G_i is an iteration process, estimates of the G_i are needed to begin the iteration. If the six-port is designed so that P_3 is primarily a function of the incident wave, then G_3 will be small. Also, we have assumed that Γ_1 is small. Under these conditions, estimates of the G_i may be obtained by letting

$$G_3 = \Gamma_1 = 0. \qquad (19)$$

Then eq (8) reduces to

$$\delta_{i\ell} = |1 + G_i\Gamma_\ell|^2 = g_{i\ell} \qquad \begin{matrix} i = 4,5,6; \\ \ell = 2,3,4 \end{matrix} \quad (20)$$

which has been expanded in eq (12). Let the three remaining terminations have a large constant reflection coefficient magnitude such as for three offset shorts. When $|\Gamma_\ell|^2$ = constant for $\ell = 2,3,4$, the three equations in eq (20) combine to give

$$\delta_{i2} - \delta_{i3} = 2G_i'\,(\Gamma_2'-\Gamma_3') - 2G_i''(\Gamma_2''-\Gamma_3'') \qquad (21)$$

$$\delta_{i2} - \delta_{i4} = 2G_i'\,(\Gamma_2'-\Gamma_4') - 2G_i''(\Gamma_2''-\Gamma_4'') \qquad (22)$$

which can be solved for G_i' and G_i'', $i = 4,5,6$;

$$2G_i' = \frac{(\delta_{i2}-\delta_{i3})\,(\Gamma_2''-\Gamma_4'') - (\delta_{i2}-\delta_{i4})\,(\Gamma_2''-\Gamma_3'')}{(\Gamma_2'-\Gamma_3')\,(\Gamma_2''-\Gamma_4'') - (\Gamma_2'-\Gamma_4')\,(\Gamma_2''-\Gamma_3'')}, \qquad (23)$$

$$-2G_i'' = \frac{(\Gamma_2'-\Gamma_3')\,(\delta_{i2}-\delta_{i4}) - (\Gamma_2'-\Gamma_4')\,(\delta_{i2}-\delta_{i3})}{(\Gamma_2'-\Gamma_3')\,(\Gamma_2''-\Gamma_4'') - (\Gamma_2'-\Gamma_4')\,(\Gamma_2''-\Gamma_3'')}. \qquad (24)$$

Since all quantities on the right of eq (23) and eq (24) are known, estimates of G_i ($i = 4,5,6$) can be calculated from these equations.

When one of the terminations is a flat short, and another termination is an open, eqs (23) and (24) can be simplified. Let

$\Gamma_2 = 1$ (open), $\Gamma_3 = -1$ (short).

Then $\Gamma_2'' = \Gamma_3'' = 0$, and eq (23) and eq (24) reduce to

$$G_i' = \frac{\delta_{i2} - \delta_{i3}}{4} \tag{25}$$

$$G_i'' = \frac{2(\delta_{i2}-\delta_{i4}) - (1-\Gamma_4')(\delta_{i2}-\delta_{i3})}{4\Gamma_4''} \; . \tag{26}$$

Note that the value of G_i' is independent of Γ_4. It is possible to obtain G_i'' independent of Γ_4 also. For the short ($\Gamma_3 = -1$), eq (20) gives

$$\delta_{i3} = (1-G_i')^2 + G_i''^2 \tag{27}$$

from which

$$G_i''^2 = \delta_{i3} - (1-G_i')^2 \tag{28}$$

where G_i' is obtained from eq (25). This gives G_i'' independent of Γ_4 except for a choice of sign. The sign of G_i'' can be chosen to agree with that obtained for an ideal six-port corresponding to the design being used.

Equations (23) and (24), or eqs (25) and (26) or eq (28) give estimates of the G_i ($i = 4,5,6$) to begin the iterative solution of eq (8) for the actual value of G_i.

IV. EQUATIONS FOR Γ

Once the G_i are determined, the ratios $|A_i|^2/A_3|^2$ can be calculated from eq (7) . Call these ratios K_i;

$$K_i = \frac{|A_i|^2}{|A_3|^2} = \frac{P_{i1}}{P_{31}} \frac{|1 + G_3\Gamma_1|^2}{|1 + G_i\Gamma_1|^2} \; , \qquad i = 4,5,6. \tag{29}$$

Then eq (7) can be used to obtain the reflection coefficient Γ_u of any other termination conn connected to the reference plane;

$$\frac{P_i}{P_3} = K_i \frac{|1 + G_i\Gamma_u|^2}{|1 + G_3\Gamma_u|^2} \qquad i = 4,5,6. \tag{30}$$

The three equations given by eq (30) yield Γ_u.

With the G_i and K_i known, there are several ways to calcualte Γ_u. The most accurate value of Γ_u is obtained by iterating the three equations in eq (30) to solve for the two unknown components Γ_u' and Γ_u'' of Γ_u. A less accurate but closed linear solution may be obtained from the three equations in eq (30) by considering Γ_u', Γ_u'', $|\Gamma_u|^2$ to be three independent unknowns. A different linear solution can be obtained from eq (4). These three different ways of calculating Γ_u are outlined below.

A. Iterating to Find Γ' and Γ''.

The solution of eq (30) for Γ_u is similar to the solution of eq (8) for the G_i. Using eq (9) in eq (30), it can be rewritten

$$\rho_i \, g_3 = g_i, \qquad i = 4,5,6, \quad (31)$$

where the second subscript on g has been dropped and ρ_i is defined as

$$\rho_i \equiv \frac{P_i}{P_3 \, K_i}, \qquad i = 4,5,6. \quad (32)$$

Define f_i as

$$f_i = \rho_i \, g_3 - g_i = 0, \qquad i = 4,5,6, \quad (33)$$

and expand f_i in a Taylor series about the best estimate of Γ_u;

$$f_i = f_{oi} + \frac{\partial f_i}{\partial \Gamma_u'} \Delta\Gamma_u' + \frac{\partial f_i}{\partial \Gamma_u''} \Delta\Gamma_u'' \qquad i = 4,5,6, \quad (34)$$

where f_{oi} is the value of f_i calculated from eq (33) using the best estimate of Γ_u. The partial derivatives

$$\frac{\partial f_i}{\partial \Gamma_u'} = \rho_i \frac{\partial g_3}{\partial \Gamma_u'} - \frac{\partial g_i}{\partial \Gamma_u'} = 2(\rho_i |G_3|^2 - |G_i|^2) \, \Gamma_u' + 2(\rho_i G_3' - G_i') \quad (35)$$

$$\frac{\partial f_i}{\partial \Gamma_u''} = \rho_i \frac{\partial g_3}{\partial \Gamma_u''} - \frac{\partial g_i}{\partial \Gamma_u''} = 2(\rho_i |G_3|^2 - |G_i|^2) \, \Gamma_u'' - 2(\rho_i G_3'' - G_i'') \quad (36)$$

for i = 4,5,6 are also calculated using the same best estimate of Γ_u. The three equations represented by eq (34) are solved for the two unknowns $\Delta\Gamma_u'$ and $\Delta\Gamma_u''$ which are used to improve the previous estimate of Γ_u. The iteration is repeated until $\Delta\Gamma_u'$ and $\Delta\Gamma_u''$ become insignificant.

An initial estimate of Γ_u to begin the iteration with can be obtained from either of the two linear solutions given below.

B. Linear Solution of Γ', Γ'', and $|\Gamma|^2$.

A closed linear solution of eq (30) can be obtained by writing eq (30) in the form of eq (31) and expanding with eq (12). This leads to

$$\rho_i[1+2G_3'\Gamma_u' - 2G_3''\Gamma_u'' + |G_3|^2 \, |\Gamma_u|^2] = 1+2G_i'\Gamma_u' - 2G_i''\Gamma_u'' + |G_i|^2 \, |\Gamma_u|^2 \quad (37)$$

or

$$1-\rho_i = 2(\rho_i G_3' - G_i') \, \Gamma_u' - 2(\rho_i G_3'' - G_i'')\Gamma_u'' + (\rho_i |G_3|^2 - |G_i|^2)|\Gamma_u|^2, \qquad i = 4,5,6. \quad (38)$$

The three equations represented by eq (38) are linear in the three quantities Γ_u', Γ_u'', $|\Gamma_u|^2$. The solution for these quantities is therefore straightforward. Note that the coefficients of Γ_u', Γ_u', and $|\Gamma_u|^2$ are the same terms needed to calculate the partials in eqs (35) and (36).

C. Constant Matrix Solution for Γ, Γ'', and $|\Gamma|^2$.

A closed matrix solution for Γ', Γ'', and $|\Gamma|^2$ can be obtained directly from eqs. (1), (2), or (4). A derivation for these quantities beginning with eq (1) is given by Hoer [3]. A similar derivation beginning with eq (4) leads to the matrix equation

$$|a|^2 \begin{bmatrix} 1 \\ |\Gamma|^2 \\ \Gamma' \\ \Gamma'' \end{bmatrix} = \underset{\sim}{G} \begin{bmatrix} P_3 \\ P_4 \\ P_5 \\ P_6 \end{bmatrix} \tag{39}$$

where $\underset{\sim}{G}$ is a real four-by-four matrix which is a function only of the calibration constants $|A_3|$, G_i, and K_i;

$$\underset{\sim}{G} = \frac{1}{|A_3|^2} \begin{bmatrix} 1 & |G_3|^2 & 2G_3' & -2G_3'' \\ K_4 & K_4|G_4|^2 & 2K_4G_4' & -2K_4G_4'' \\ K_5 & K_5|G_5|^2 & 2K_5G_5' & -2K_5G_5'' \\ K_6 & K_6|G_6|^2 & 2K_6G_6' & -2K_6G_6'' \end{bmatrix}^{-1} \tag{40}$$

The reflection coefficient is obtained from elements 1, 3, and 4 of the left column vector in eq (39), i.e., from $|a|^2$, $|a|^2\Gamma'$, and $|a|^2\Gamma''$;

$$\Gamma = \frac{\Gamma'|a|^2 + j\,\Gamma''|a|^2}{|a|^2} \tag{41}$$

Since $|A_3|^2$ in eq (40) cancels when calculating Γ with eq (41), it can be set equal to one.

D. Comparison of Solutions for Γ

The iterative method in A is more accurate than either of the closed linear solutions described in B or C. This is because all three equations in eq (30) are used to find only two instead of three unknowns. When Γ', Γ'', and $|\Gamma|^2$ are considered to be three independent unknowns, these three values will not usually satisfy the relation

$$\Gamma'^2 + \Gamma''^2 = |\Gamma|^2.$$

However, the loss in accuracy may not be significant or worth the extra time required to iterate.

One advantage of solution C over the other two solutions is that the matrix $\underset{\sim}{G}$ is independent of Γ and therefore needs to be calculated only once at a given frequency for any number of measurements.

V. CALIBRATION EQUATIONS, v and i PARAMETERS

Instead of expressing the equations in terms of the reflection coefficient at the reference plane, it is sometimes more convenient to write the equations in terms of impedance. This is especially true when a high quality flat short is one of the four standard terminations used in calibrating the six-port. If in eq (1) we let

$$v = a+b \tag{42}$$

$$iZ_o = a-b \tag{43}$$

then eq (1) becomes

$$P_i = |C_i v + D_i i Z_o|^2 , \qquad i = 3...6, \tag{44}$$

where v,i, and Z_o are the voltage, current, and characteristic impedance at the reference plane, and

$$C_i = \frac{A_i + B_i}{2}, \quad D_i = \frac{A_i - B_i}{2} \qquad i = 3...6. \tag{45}$$

Now add a subscript ℓ as before to indicate the termination being used, and factor out $D_i i Z_o$ from eq (44) to obtain an expression similar to eq (4);

$$P_{i\ell} = |D_i i_\ell Z_o|^2 \; |1 + H_i z_\ell|^2 \qquad i = 3...6; \; \ell = 1...4, \tag{46}$$

where z_ℓ is the impedance Z_ℓ of the termination at the reference plane divided by Z_o, and H_i is a new constant describing the six-port;

$$z_\ell = \frac{v_\ell}{i_\ell Z_o} = \frac{Z_\ell}{Z_o} \tag{47}$$

$$H_i = \frac{C_i}{D_i} = \frac{1 + G_i}{1 - G_i} . \tag{48}$$

Again assume that P_3 is primarily a function of the incident wave, a, so that P_3 will never be zero. Dividing eq (46) by $P_{3\ell}$ gives

$$\frac{P_{i\ell}}{P_{3\ell}} = \frac{|D_i|^2}{|D_3|^2} \frac{|1 + H_i z_\ell|^2}{|1 + H_3 z_\ell|^2} \qquad i = 4,5,6; \; \ell = 1...4. \tag{49}$$

For the first termination, eq (49) gives

$$\frac{P_{i1}}{P_{31}} = \frac{|D_i|^2}{|D_3|^2} \frac{|1 + H_i z_1|^2}{|1 + H_3 z_1|^2} \qquad i = 4,5,6. \tag{50}$$

Finally, assume again that z_1 of the first termination is such that none of the P_{i1}, are zero. Then dividing eq (49) by eq (50) yields

$$\delta_{i\ell} = \frac{P_{i\ell}\, P_{31}}{P_{3\ell}\, P_{i1}} = \left| \frac{1 + H_i z_\ell}{1 + H_3 z_\ell} \cdot \frac{1 + H_3 z_1}{1 + H_i z_1} \right|^2 \qquad \begin{matrix} i = 4,5,6 \\ \ell = 2,3,4. \end{matrix} \tag{51}$$

In this solution of this equation for the H_i is identical to the solution of eq (8) for the G_i. Initial estimates of the H_i can be obtained from initial estimates of the G_i through eq (48), or from equation given below.

VI. SIMPLIFIED CALIBRATION EQUATIONS

A. Ideal Short

Choose the first termination to be a high quality flat short so that it can be assumed that Z_1=0. Then eq (51) becomes

$$\delta_{i\ell} = \frac{|1 + H_i z_\ell|^2}{|1 + H_3 z_\ell|} \qquad \begin{matrix} i = 4,5,6; \\ \ell = 2,3,4. \end{matrix} \tag{52}$$

Since this equation assumes that none of the P_{i1} are zero, none of the sidearms can be proportional to v = a+b since v is zero when a short is at the reference plane. Although eq (52) is also a nonlinear equation, it is somewhat easier to solve for the calibration constants than in eq (51) or eq (8).

No assumption about the remaining three terminations are made in eq (52). The value of Z_ℓ for these three remaining known terminations could be an open, a reactance, and a resistance. If these three terminations are sufficiently ideal, the solution can be simplified as described below.

B. Ideal Open, Reactance, and Resistance

If the second termination is an open circuit, z_ℓ becomes infinite so eq (52) gives

$$\delta_{i2} = \frac{|H_i|^2}{|H_3|^2} \qquad i = 4,5,6. \tag{53}$$

Let the third termination be a pure reactance, and the fourth termination be a pure resistance. Then if we define

$$H_i = H_i' + jH_i'' \tag{54}$$

$$z_\ell = R_\ell + jX_\ell, \tag{55}$$

and assume that Z_0 is real, eq (52) yields

$$\delta_{i3} = \frac{|1 + H_i JX_3|^2}{|1 + H_3 jX_3|^2}\ , \qquad i = 4,5,6, \tag{56}$$

$$\delta_{i4} = \frac{|1 + H_i R_4|^2}{|1 + H_3 R_4|^2}\ , \qquad i = 4,5,6. \tag{57}$$

Using eqs (53) and (54) in eqs (56) and (57) leads to

$$\delta_{i3} = \frac{1 - 2 H_i'' X_3 + \delta_{i2} |H_3|^2 X_3^2}{1 - 2 H_3'' X_3 + |H_3|^2 X_3^2} \qquad i = 4,5,6, \quad (58)$$

$$\delta_{i4} = \frac{1 + 2 H_i' R_4 + \delta_{i2} |H_3|^2 R_4^2}{1 + 2 H_3' R_4 + |H_3|^2 R_4^2} \qquad i = 4,5,6 \quad (59)$$

Solving eq (58) for H_i'' and eq (59) for H_i' yields

$$H_i'' = \frac{1-\delta_{i3}}{2 X_3} + \delta_{i3} H_3'' + X_3 \frac{(\delta_{i2} - \delta_{i3})}{2} |H_3|^2 \qquad (60)$$

$$H_i' = \frac{\delta_{i4} - 1}{2R_4} + \delta_{i4} H_3' + R_4 \frac{(\delta_{i4} - \delta_{12})}{2} |H_3|^2 \qquad (61)$$

for i = 4,5,6. Finally, adding the square of eq (60) to the square of eq (61) and substituting into eq (53) gives

$$(H_i'')^2 + (H_i')^2 = |H_i|^2 =$$

$$\delta_{i2}|H_3|^2 = \left[\frac{1-\delta_{i3}}{2 X_3} + \delta_{i3} H_3'' + X_3 \frac{(\delta_{i2} - \delta_{i3})}{2} |H_3|^2\right]^2$$

$$+\left[\frac{\delta_{i4}-1}{2 R_4} + \delta_{i4} H_3' + R_4 \frac{(\delta_{i4} - \delta_{i2})}{2} |H_3|^2\right]^2 \qquad i = 4,5,6. \quad (62)$$

The three equations represented by eq (62) can be solved for H_3' and H_3''. The remaining H_i' and H_i'' for i = 4,5,6 are then obtained from eqs (60) and (61). Although eq (62) is a nonlinear equation and must be solved by iteration, the iteration is faster than when solving eqs (8), (51) and (52) because only two unknowns are being solved for.

C. Initial Estimates of H_3

We have already noted that G_3 is small for a six-port designed so that P_3 is primarily a function of the incident wave. For this design eq (48) gives

$$H_3 \simeq 1 + j0.$$

This value of H_3 is a good estimate to use in beginning the iterative solution of eq (62).

VII. EQUATIONS FOR Z

Once the H_i are determined, the ratios $|D_i|^2/|D_3|^2$ can be calculated from eq (50). Call these ratios small k_i;

$$k_i = \frac{|D_i|^2}{|D_3|^2} = \frac{P_{i1}}{P_{31}} \frac{|1 + H_3 z_1|^2}{|1 + H_i z_1|^2} \qquad i = 4,5,6. \quad (64)$$

Then eq (50) can be used to obtain the normalized impedance z_u of any other termination connected to the reference plane;

$$\frac{P_i}{P_3} = k_i \frac{|1 + H_i z_u|^2}{|1 + H_3 z_u|^2} \qquad i = 4,5,6. \quad (65)$$

These three equations can be solved for z_u in the same manner as eq (30) was solved for Γ_u. One can iterate to find R_u and X_u as outlined in section IV A, or derive a linear solution for R_u, X_u, and $|z_u|^2$ as outlined in section IV B. A linear solution for $|v|$, $|iZ_o|$, R_u and X_u is similar to that out-lined in section IV C and is given below.

A. Constant Matrix Solution for R, X, and $|z|^2$.

A closed matrix solution R, X, and $|z|^2$ at the reference plane can be obtained from eq (46). Dropping the subscript ℓ and expanding eq (46) gives

$$P_i = |D_i i Z_o|^2 \left[1 + 2H_i' R - 2H_i'' X + |H_i|^2 |z|^2\right]. \quad (66)$$

Using eq (64) in eq (66),

$$P_i = |D_3|^2 |iZ_o|^2 \left[K_i + 2K_i H_i' R - 2K_i H_i'' X + K_i |H_i|^2 |z|^2\right], \qquad i = 3\ldots6. \quad (67)$$

The four equations represented by eq (67) lead to the matrix equation

$$|iZ_o|^2 \begin{bmatrix} |z|^2 \\ 1 \\ R \\ X \end{bmatrix} = \underset{\sim}{H} \begin{bmatrix} P_3 \\ P_4 \\ P_5 \\ P_6 \end{bmatrix} \quad (68)$$

where $\underset{\sim}{H}$ is a constant matrix similar to $\underset{\sim}{G}$ and is a function only of the calibration constants $|D_3|$, H_i, and k_i;

$$
\underset{\sim}{H} = \frac{1}{|D_3|^2} \begin{bmatrix} |H_3|^2 & 1 & 2\,H_3' & -2\,H_3'' \\ k_4\,|H_4|^2 & k_4 & 2\,k_4\,H_4' & -\,2\,k_4\,H_4'' \\ k_5\,|H_5|^2 & k_5 & 2\,k_5\,H_5' & -\,2\,k_5\,H_5'' \\ k_6\,|H_6|^2 & k_6 & 2\,k_6\,H_6' & -\,2\,k_6\,H_6'' \end{bmatrix}^{-1} \tag{69}
$$

The impedance is obtained from elements 2, 3, and 4 of the left column vector in eq (68);

$$
z_u = \frac{Z_u}{Z_o} = \frac{|iZ_o|^2\,R + J\,|iZ_o|^2 X}{|iZ_o|^2} \quad . \tag{70}
$$

Since $|D3|^2$ in eq (69) cancels when calculating z_u with eq (70), it can be set equal to one.

It can be shown that $\underset{\sim}{H}$ and $\underset{\sim}{G}$ are related by [3]

$$
\underset{\sim}{H} = \underset{\sim}{K}\;\underset{\sim}{G} \tag{71}
$$

where

$$
\underset{\sim}{K} = \begin{bmatrix} 1 & 1 & 2 & 0 \\ 1 & 1 & -2 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 2 \end{bmatrix} . \tag{72}
$$

VIII. CONCLUSION

Equations have been derived for determining the calibration constant of a six-port reflectometer and also for calculating Γ or z once these constants are known. Further work needs to be done to determine how much accuracy is lost when using the closed linear solutions for Γ or z instead of the nonlinear iterative solution.

The equations given in this report can be extended to the case of more than 6 detectors or when more than four known terminations are available by letting i = 3,4,5,6,7,... and/or ℓ = 1,2,3,4,5....

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APPENDIX A

This appendix outlines a solution of eq (15) for the eight ΔG, and also gives useful some approximations to simplify the solution.

If the first standard termination has a reflection coefficient $\Gamma_1 \simeq 0$, then eqs (12) and (17) become

$$g_{i1} \simeq 1, \qquad i = 3...6 \quad \text{(A1)}$$

$$\frac{\partial g_{i1}}{\partial G_i'} \simeq \frac{\partial g_{i1}}{\partial G_i''} \simeq 0 \qquad i = 3...6, \quad \text{(A2)}$$

which can be used to simplify the partial derivative in eq (16) to

$$\begin{aligned} \frac{\partial f_{i\ell}}{\partial G_3'} &= \delta_{i\ell} \frac{\partial g_{3\ell}}{\partial G_3'} \\ \frac{\partial f_{i\ell}}{\partial G_3''} &= \delta_{i\ell} \frac{\partial g_{3\ell}}{\partial G_3''} \\ \frac{\partial f_{i\ell}}{\partial G_i'} &= - \frac{\partial g_{i\ell}}{\partial G_i'} \\ \frac{\partial f_{i\ell}}{\partial G_i''} &= - \frac{\partial g_{i\ell}}{\partial G_i''} \end{aligned} \qquad \begin{aligned} i &= 4,5,6 \\ \ell &= 2,3,4. \end{aligned} \quad \text{(A3)}$$

To simplify writing, define

$$\begin{aligned} K_{i\ell} &\equiv \frac{\partial g_{i\ell}}{\partial G_i'} = 2\Gamma_\ell' + 2G_i'|\Gamma_\ell|^2 \\ L_{i\ell} &\equiv \frac{\partial g_{i\ell}}{\partial G_i''} = -2\Gamma_\ell'' + 2G_i''|\Gamma_\ell|^2 \end{aligned} \qquad \begin{aligned} i &= 3...6, \\ \ell &= 1...4. \end{aligned} \quad \text{(A4)}$$

where eq (12) was used to obtain the partials. Substituting eqs (A3) and (A4) into eq (15) gives

$$f_{oi\ell} + \delta_{i\ell} K_{3\ell} \Delta G_3' + \delta_{i\ell} L_{3\ell} \Delta G_3'' = K_{i\ell} \Delta G_i' + L_{i\ell} \Delta G_i'' \qquad \begin{aligned} i &= 4,5,6; \\ \ell &= 2,3,4. \end{aligned} \quad \text{(A5)}$$

One way of solving this equation for each ΔG is to first eliminate $\Delta G_i'$ and $\Delta G_i''$ for $i = 4,5,6$, and then solve for $\Delta G_3'$ and $\Delta G_3''$. The two equations obtained from eq (A5) for measurements with termination numbers two and three can be written as one matrix equation;

$$\begin{bmatrix} f_{oi2} \\ f_{oi3} \end{bmatrix} + \begin{bmatrix} \delta_{i2} K_{32} & \delta_{i2} L_{32} \\ \delta_{i3} K_{33} & {}_{i3} L_{33} \end{bmatrix} \begin{bmatrix} \Delta G_3' \\ \Delta G_3'' \end{bmatrix} = \begin{bmatrix} K_{i2} & L_{i2} \\ K_{i3} & L_{i3} \end{bmatrix} \begin{bmatrix} \Delta G_i' \\ \Delta G_i'' \end{bmatrix} \qquad i = 4,5,6. \quad \text{(A6)}$$

or simply

$$\vec{F}_i + \underset{\sim}{M}_i \vec{\Delta G}_3 = \underset{\sim}{N}_i \vec{\Delta G}_i , \qquad i = 4,5,6 \quad \text{(A7)}$$

where the matrix symbols in (A7) are defined by the corresponding matrices in eq (A6). Solving eq (A7) for $\vec{\Delta G}_i$,

$$\vec{\Delta G}_i = \underset{\sim}{N}_i^{-1} \vec{F}_i + \underset{\sim}{N}_i^{-1} \underset{\sim}{M}_i \vec{\Delta G}_3 \qquad i = 4,5,6. \quad \text{(A8)}$$

Equations (A5) for the measurement with termination number four can also be written as a matrix equation;

$$f_{oi4} + \underline{S}_i \vec{\Delta G}_3 = \underline{T}_i \vec{\Delta G}_i \qquad i = 4,5,6 \quad \text{(A9)}$$

where $\underline{S}_i$ and $\underline{T}_i$ are 1-by-2 matrices defined by

$$\underline{S}_i = \begin{bmatrix} \delta_{i4} K_{34} & \delta_{i4} L_{34} \end{bmatrix} \quad \text{(A10)}$$

$$\underline{T}_i = \begin{bmatrix} K_{i4} & L_{i4} \end{bmatrix}. \quad \text{(A11)}$$

Substituting eq (A8) into eq (A9) yields

$$f_{oi4} + \underline{S}_i \vec{\Delta G}_3 = \underline{T}_i \left(\underset{\sim}{N}_i^{-1} \vec{F}_i + \underset{\sim}{N}_i^{-1} \underset{\sim}{M}_i \vec{\Delta G}_3 \right) \qquad i = 4,5,6 \quad \text{(A12)}$$

or

$$f_{oi4} + \left(\underline{S}_i - \underline{T}_i \underset{\sim}{N}_i^{-1} \underset{\sim}{M}_i \right) \vec{\Delta G}_3 = \underline{T}_i \underset{\sim}{N}_i^{-1} \vec{F}_i \qquad i = 4,5,6. \quad \text{(A13)}$$

The three equations represented by eq (A13) can be combined into one matrix equation;

$$\begin{bmatrix} f_{o44} \\ f_{o54} \\ f_{o64} \end{bmatrix} + \begin{bmatrix} \underline{S}_4 - \underline{T}_4 \underset{\sim}{N}_4^{-1} \underset{\sim}{M}_4 \\ \underline{S}_5 - \underline{T}_5 \underset{\sim}{N}_5^{-1} \underset{\sim}{M}_5 \\ \underline{S}_6 - \underline{T}_6 \underset{\sim}{N}_6^{-1} \underset{\sim}{M}_6 \end{bmatrix} \overrightarrow{\Delta G}_3 = \begin{bmatrix} \underline{T}_4 \underset{\sim}{N}_4^{-1} \vec{F}_4 \\ \underline{T}_5 \underset{\sim}{N}_5^{-1} \vec{F}_5 \\ \underline{T}_6 \underset{\sim}{N}_6^{-1} \vec{F}_6 \end{bmatrix} \tag{A14}$$

or simply

$$\vec{U} + \underline{V}\, \overrightarrow{\Delta G}_3 = \vec{W}. \tag{A15}$$

The solution for $\overrightarrow{\Delta G}_3$ is

$$\overrightarrow{\Delta G}_3 = (\underline{V}^T \underline{V})^{-1}\ \underline{V}^T (\vec{W} - \vec{U}). \tag{A16}$$

With $\overrightarrow{\Delta G}_3$ known, the remaining $\overrightarrow{\Delta G}_i$ for i = 4,5,6 can be obtained from eq (A8).

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET**	1. PUBLICATION OR REPORT NO. NBS TN-1012	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Calibrating a Six-Port Reflectometer with Four Impedance Standards

5. Publication Date: March 1979

6. Performing Organization Code: 724.01

7. AUTHOR(S)

Cletus A. Hoer

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No.: 7241403

11. Contract/Grant No.

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*

13. Type of Report & Period Covered: Tech Note

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report is a theoretical study showing how four terminations of known impedance can be used to calibrate a six-port reflectometer for measuring other terminations of unknown impedance. The equations for obtaining the calibration constants are exact but nonlinear, requiring an iterative solution. Several ways are described for using these constants to calculate the impedance of terminations being measured with the six-port reflectometer.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Calibration; impedance; reflection coefficient; reflectometer; six-port.

18. AVAILABILITY [X] Unlimited

[ ] For Official Distribution. Do Not Release to NTIS

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[ ] Order From National Technical Information Service (NTIS) Springfield, Virginia 22151

19. SECURITY CLASS (THIS REPORT): UNCLASSIFIED

20. SECURITY CLASS (THIS PAGE): UNCLASSIFIED

21. NO. OF PAGES: 24

22. Price: $1.20

☆U.S. GOVERNMENT PRINTING OFFICE: 1979-0-677-072/1259 USCOMM-DC 29042-P

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